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HANDLING QUALITIES EVALUATIONS OF UNMANNED AIRCRAFT SYSTEMS

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HANDLING QUALITIES EVALUATIONS OF UNMANNED AIRCRAFT SYSTEMS

Kevin Longeuay^{*} and Christopher Baughman[†]

Since 1969, the Cooper-Harper Rating Scale has been used widely in flight test to qualitatively evaluate the handling qualities of manned aircraft. Within the past decade, the use and popularity of Unmanned Aircraft Systems (UAS) has expanded into military operations and commercial applications. Therefore, there is a need to understand the handling qualities of these systems when a pilot is required for in-the-loop control. Key differences in flight control systems, autonomous flight capabilities, and overall system latency in unmanned versus manned aircraft necessitate the development of approaches to enhance understanding of these systems. This paper identifies the need for Cooper-Harper evaluations of UAS, highlights the differences between manned and unmanned systems, and provides an approach to determining the Cooper-Harper evaluation of unmanned systems.

INTRODUCTION

Evaluating Handling Qualities of an Aircraft

In aircraft design, engineers need to consider both the unaugmented flying qualities of the aircraft and the handling qualities of the aircraft with a pilot in the loop. An aircraft can be very stable in all axes of flight at nominal conditions, but without proper design of handling qualities, the pilot may have difficulty controlling the aircraft in either normal operations or in “corner cases,” which are usually only found via a thorough handling qualities evaluation during flight test. These instances are often referred to as handling qualities “cliffs” in which aircraft control appears normal until a condition in which rapid degradation occurs. Best described by George Cooper and Robert Harper, handling qualities are defined as “those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role.”¹ Therefore, it is important to know the role of the aircraft in order to properly design the Pilot Vehicle Interface (PVI) to support those roles. Table 1 below provides some aircraft roles and common tasks associated with those roles.

Table 1 Common Aircraft Roles and Operational Tasks

Tasks \ Roles	Fighter/Strike	Bomber	Surveillance
Taxi	X	X	X
Takeoff	X	X	X

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Tasks \ Roles	Fighter/Strike	Bomber	Surveillance
Climb	X	X	X
Formation Flight	X	X	
Precision Strike	X	X	
Air-to-Air Combat	X		
Aerial Refueling	X	X	
Surveillance	X	X	X
Landing	X	X	X

Every aircraft needs to be able to complete takeoff, climb, and landing. Additional tasks may need to be accomplished depending on the aircraft's mission. From a handling qualities perspective, the tasks that require the tightest control of the aircraft and are the most stressful on the pilot are generally the most difficult for the pilot to perform. When coupled with critical phases of flight, close proximity to the ground or other aircraft, or releasing ordinance, the need for designing in desirable handling qualities is essential.

As an operator of the aircraft, the pilot is a part of the control loop. The pilot's involvement in the control loop is represented in the block diagram in Figure 1².

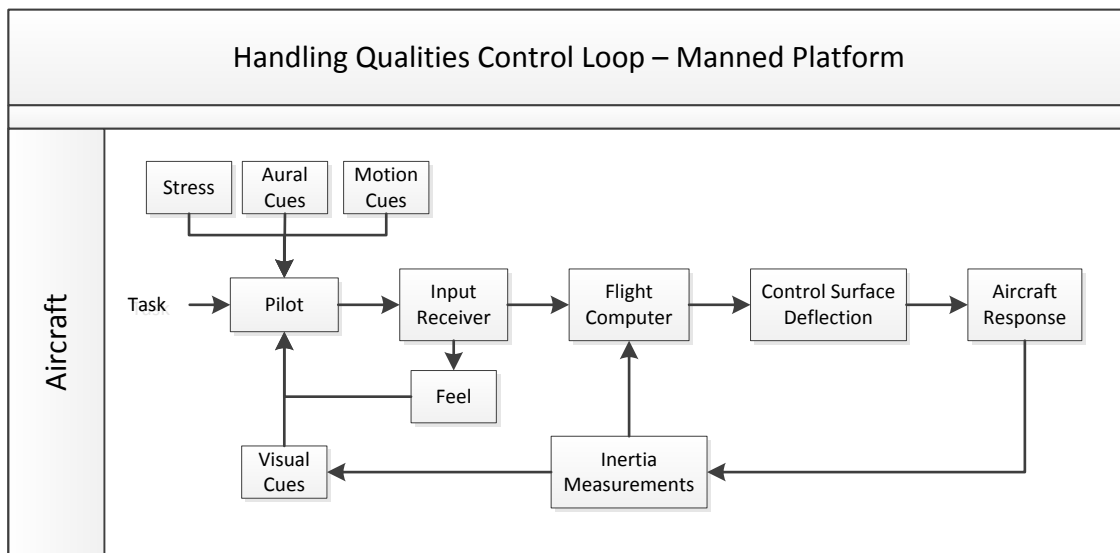


Figure 1 Handling Qualities Control Loop – Manned Platform

In a manned platform, the pilot uses aural, visual, and motion cues to provide an input to the system for a given task. Aural cues include engine response, warning indications, and aerodynamic acoustics such as buffeting which provides feedback on aerodynamic response of the aircraft. Visual cues include aircraft position relative to the horizon using forward and peripheral vision, critical aircraft parameters displayed on a Heads Up Display (HUD) or Heads Down Display (HDD), navigation referencing, and spatial referencing (for formation, air-to-air combat, and aerial refueling). Motion cues include all the forces the pilot is subjected due during maneuvering of the aircraft. These motion cues, or proprioceptive feedback, allow the pilot to “feel” the aircraft

response and apply corrective inputs accordingly. The input receiver on an aircraft traditionally consists of a single axis throttle lever to control power from the propulsion system, a two axis control stick to control pitch and roll, and a dual axis pedal system to control yaw and braking. Using these various sensory cues and the input receiver, the pilot can fine-tune the desired response of the aircraft to complete the task at hand.

Testing of handling qualities is widely performed using the Cooper-Harper rating scale. Established in 1969, the Cooper-Harper rating system evaluates handling qualities of an aircraft system by having the pilot perform operationally representative tasks within specific desired and adequate performance criteria and then providing feedback on the performance attained, the workload required, and amount of pilot compensation needed to perform the task³. This system allows the engineers to determine the handling qualities allow the pilot to achieve the operational tasks which the aircraft was designed for. After performing an operational task, the pilot uses the Cooper-Harper rating scale, shown in Figure 2. The scale provides a means to measure task performance and assess workload, which drives overall rating.

The results of a handling qualities evaluation are important in determining how well the aircraft can be controlled by the pilot. Cooper-Harper Ratings (CHR) are given numerically from 1 to 10, with Level ratings from 1 to 3. A Level 1 aircraft is described by a CHR of 1-3, and is considered to have desirable handling qualities with no deficiencies. A Level 2 aircraft will have a CHR of 4-6, with minor deficiencies that warrant improvement. In Level 2 aircraft, pilot compensation is generally relied upon to maintain safety and increase pilot performance, however this comes at a price of additional training and increased risk. A Level 3 aircraft (CHR 7-9) has significant deficiencies, in which improvements are required and control is either borderline or very difficult. A CHR of 10 indicates that the aircraft is uncontrollable. Most military aircraft exhibit Level 1 handling qualities and some have Level 2 tendencies. For example, the C-17 exhibited some Level 2 tendencies in the roll axis, even after a roll Pilot-in-the-loop Oscillation (PIO) problem was mitigated⁴. In some cases, an aircraft can have Level 2 or Level 3 handling qualities for a specific task. For the parachute extraction mission at low altitude, the C-130 demands the pilot fly precisely while in close proximity to terrain. According to one U.S. Air Force test pilot, the C-130 is "Level 2 at best, mostly Level 3."⁵ In a UAS, Level 1 handling qualities are even more elusive due to the effects of time delay and lack of proprioceptive feedback. This will be discussed later in the UAS datalink section.

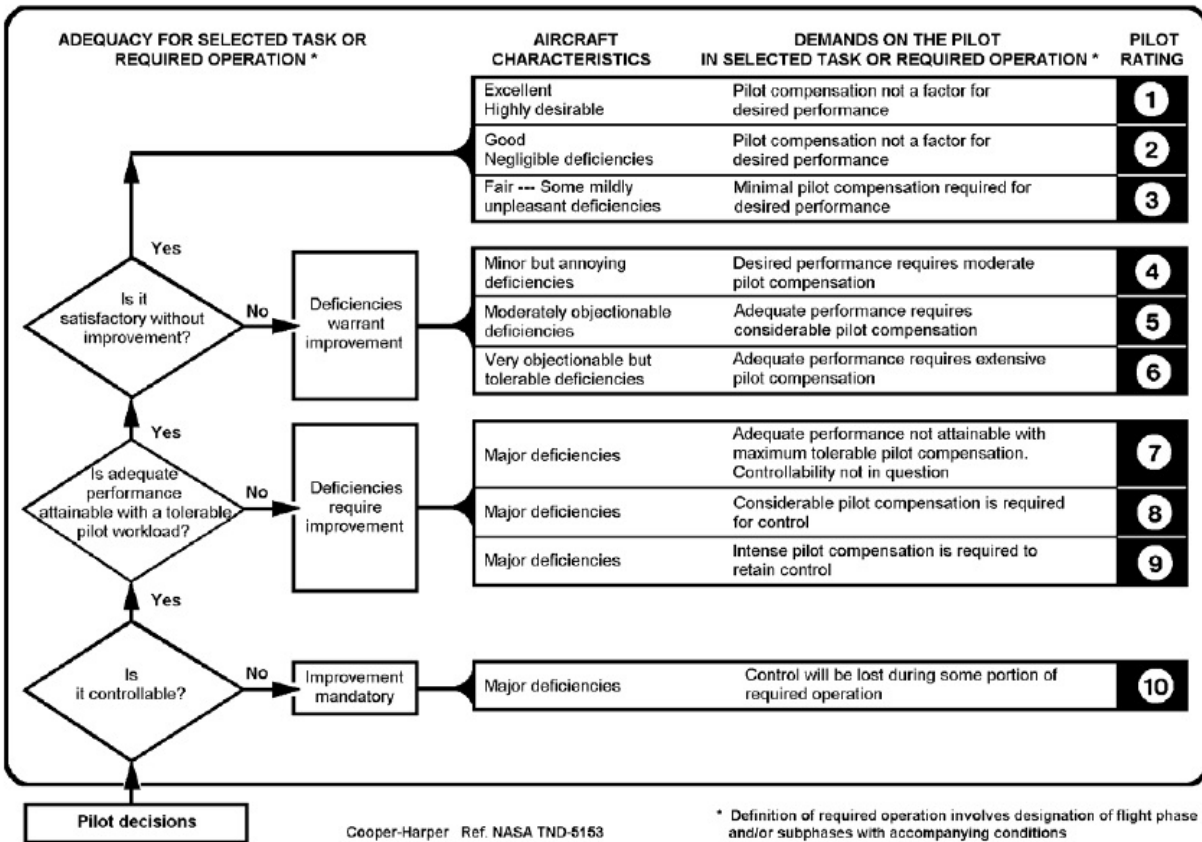


Figure 2 Cooper-Harper Rating Scale

To execute handling qualities testing, the test team needs to first determine the operational tasks required of the aircraft in order to fulfill its role in the mission. These operational tasks should be any tasks required by the pilot in order to achieve a given mission. For each task, adequate and desired performance criteria are created based on mission specific performance characteristics for the system under test. An example of performance criteria for an unmanned vehicle during a normal takeoff is listed below in Table 2:

Table 2 Example Takeoff Performance Criteria

Measure of Performance	Desired Criteria	Adequate Criteria
Pitch attitude at rotation	$5^{\circ} \pm 0.5^{\circ}$	$5^{\circ} \pm 2^{\circ}$
Airspeed	$V_{\text{climb}} \pm 2 \text{ KIAS}$	$V_{\text{climb}} \pm 3 \text{ KIAS}$
Heading Control	Runway Track $\pm 2^{\circ}$	Runway Track $\pm 5^{\circ}$
	No observed roll /yaw oscillations	No observed roll/yaw oscillations

For this task, the pilot will attempt to pitch the aircraft to $+5^{\circ}$ initially and adjust/maintain pitch attitude to maintain a target climb speed $\pm 2 \text{ KIAS}$ during the initial climb out. This task is

appropriate especially for an aircraft with an attitude-command flight control system, which will be discussed in depth later. The pilot will also attempt to maintain aircraft tracking on runway centerline through the takeoff roll until after rotation and initial turn out. After the task has completed, the pilot will determine the workload required for the performance attained and will provide any other comments relating to the task. The pilot might comment on how much force on the control stick was required, if there was a lot dead band in the stick, if the breakout force to move the stick from neutral seemed high, if applying a pitch input resulted in roll inputs as well, control harmony, stick sensitivity, or any other applicable factors. When determining workload, the pilot will consider any environmental factors that affected performance and increased pilot workload. Examples of environmental factors are high crosswind conditions, turbulence, extremely high temperatures, moisture, or standing water on the runway. Additionally, pilot compensation must be taken into consideration. Pilot compensation occurs in many forms, both mentally and physically. Some examples of this are flying a maneuver with low gains to try and stay out of the loop with the aircraft, gripping the control stick a certain way, and “leading” control inputs based on the pilot’s mental model of aircraft behavior. Pilot compensation is probably the most difficult parameter to evaluate as it requires the pilot to carefully consider and separate the effects of how and why the aircraft behaved in the manner in which it did. Additionally, the difference between minimal and moderate compensation may mean the difference between a Level 1 and Level 2 aircraft. If not properly evaluated, a Level 2 aircraft may be deemed Level 1 by missing key factors of pilot compensation.

When determining the Cooper-Harper rating for the task, it is important that the pilot maintain the proper sequencing of the Cooper-Harper scale and not rely solely on the individual rating description. Also, it is important for the pilot to rate the task immediately after it is performed. Any later changes to the pilot ratings are discouraged since the reason for the change may be biased. More information for proper use of the Cooper-Harper rating scale can be found in Cooper and Harper’s original report, written in 1969⁶.

In addition to Cooper-Harper ratings, the pilots should be encouraged to provide comments on the handling qualities of aircraft during the task. These comments should be collected as an addition to the ratings but should be in simple language (i.e., should not be translated into engineering terms or aircraft responses) and should focus on describing the difficulty in performing specific inputs and how that difficulty may or may not affect overall task performance.

Since the Cooper-Harper ratings are qualitative in nature, it is important that each test be repeated using multiple pilots. Using multiple pilots provides a range of evaluations and some pilots may identify poor areas of handling qualities that were overlooked by other pilots.

UAS Expansion in Military Operations

UAS fall into five groups, from small UAS (sUAS) to larger Remotely-Piloted Aircraft (RPA) that fly at higher altitudes, faster speeds, and have longer ranges. Figure 3 below outlines Groups 1-5.

UAS Groups		Maximum Weight (lbs)	Normal Operating Altitude (ft)	Speed (kts)	Representative Aircraft
sUAS	Group 1	0-20	< 1,200 AGL	<100	Raven (RQ-11) Wasp
	Group 2	21-55	< 3,500 AGL	< 250	Scan Eagle
	Group 3	< 1,320	< FL 180	< 250	Currently No USAF Program of Record for this Category
RPA	Group 4	> 1,320	< FL 180	Any Airspeed	Predator (MQ-1)
	Group 5	> 1,320	> FL 180	Any Airspeed	Reaper (MQ-9) Global Hawk (RQ-4)

Figure 3 Groups of UAS⁷

Generally, Groups 4 and 5 are considered RPA, while Groups 1-3 are categorized as small UAS, or sUAS. UAS have been developed and used since World War II, and although at face value they may be regarded as newcomers to flight test circles, only recently has the industry experienced broad growth. The Association for Unmanned Vehicle Systems International, or AUVTI, recognizes 715 companies which produce over 2400 platforms⁸. Among these systems, a majority, especially those in Groups 4-5 employ higher levels of autonomy - some almost exclusively - in order to accomplish their missions.

The Air Force has put a great deal of thought into not only categorizing UAS and RPA, but also in defining its vision for the next 25 years with regard to integrating unmanned vehicles into airpower doctrine. On the other hand, very little has been done to define autonomy and categorize the appropriate levels of autonomy when dealing with a given core function. Levels of control for the UAS have been defined, but this is not to be confused with levels of autonomy which define specifically how a vehicle operates and its ability to observe, orient, decide, and act (OODA). More specifically, how “in the loop” does the vehicle require its pilot or operator to be?

Researchers at Air Force Research Laboratory (AFRL) attempted to tackle this issue in 2002 by defining levels of autonomy, which they defined as 1) the ability to generate one’s own purposes without any instruction from the outside, and 2) having free will⁹. AFRL used three metrics to measure the autonomy of the UAS, graduated on ten levels – perception/situational awareness, analysis/decision making, and communication/cooperation.

Why in the Loop?

Before delving into how we test the handling qualities of a pilot-in-the-loop UAS, we must first answer the question “why design the system with the pilot in the loop?” The concept of a robotic airplane can immediately conjure up flashbulb memories of Hollywood films in which robots become “self-aware,” multi-task, and execute missions with capabilities far beyond that of even the most storied of superheroes. Reality dictates that as of 2015, AI is not quite that sophisticated. Further, removal of pilot from the airplane leads to a tendency to separate UAS from

manned aircraft. While in many cases this is warranted, there still exist core functions in which pilot in the loop control is appropriate and necessary.

Unmanned systems are one of three configurations: remotely-piloted, fully-autonomous, or a mixture of the two. The remotely-piloted system uses a controlling station interfaced with a pilot that sends flight control commands to the aircraft using a data link. A fully-autonomous system also uses a controlling station but instead of piloted control, a mission plan is sent to the aircraft which is then processed by the onboard flight control system and executed without any further uplinked commands. The mission may be monitored from any number of terminals and changes to the mission plan can be sent from the control station via an operator but the operator does not have direct control of the aircraft. This can also be thought of as pilot “on the loop.” Fully autonomous systems, however, are limited in mission scope to intelligence, surveillance, and reconnaissance (ISR) missions and do not allow for combat missions, at least in today’s battlespace.

Although UAS depend on autonomy a great deal, there is much to be gained by having a pilot in the loop. First, flight testing of aircraft performance and flying qualities is greatly facilitated by having a pilot in the loop. However, design for mission suitable aircraft are seldom, and should not be designed simply to optimize test and evaluation. Even higher levels of autonomous flight that require minimal pilot interaction with flight controls are achieved via the airplane interacting with the four basic forces of flight, and must achieve stability and control via algorithms which compensate for the effects in that domain. No feedback loop or computer algorithm can deliver the same qualitative feedback as a pilot.

The deployment of weapon systems demands a pilot in the loop. As an integral part of the kill chain, it is ultimately the pilot who makes the final decision on weapon employment. Although any process can be automated, there is far too much at stake when weapon employment is involved. Just as the decision whether to take lives should not be automated, the final authority for weapon release should rest with a human. This is not to infer that humans are infallible, but acts of war demand accountability and responsibility, and neither can be delegated to AI. In the commercial sector, missions do not require deliberate choices between life and death; however the automation must execute its mission at or better than the human can in all conditions.

Lastly, takeoff and landing are the most flight critical portions of the mission. Between fiscal year 2000 and 2013, 15% of MQ-1[®] and MQ-9[®] Class A mishaps occurred during the takeoff and landing phase, many of those in the form of PIO during the landing phase¹⁰. Due to this abnormally high landing accident rate, many unmanned systems already employ automatic takeoff and landing systems. In fact, similar systems have been developed for manned aircraft. These takeoff and landing systems (TALS) must work 100% of the time otherwise the systems will not be reliable and will not be used operationally. The systems that have already been developed for land based operations have proven to be satisfactory in some aspects. However, as more sophisticated recovery algorithms continue to evolve, there will always be a need to understand at the most basic level how the aircraft gets safely back to the runway. In some cases, pilot-in-the-loop design may help mitigate risk initially. As systems begin to integrate with manned platforms in FAA-controlled airspace, they will need to afford the user flexibility to see-think-act in a way that meets or exceeds the ability of the human pilot. As of 2015, the operation of an unmanned aircraft at any airfield is a major event. Notices to Airmen (NOTAMs) are issued, Temporary Flight Restrictions (TFRs) are enacted, radio calls are made; and for all intents and purposes everyone operates under the understanding that operations are anything but normal. Operating with a pilot in the loop, talking on the radio, controlling the aircraft is simply one way to bridge the gap for the time being.

Based on these reasons, it is important to maintain a pilot in the loop of the UAS, especially with the growing importance of the UAS as a military asset and with the ever increasing scope of the UAS. Since the pilot is in the loop of the UAS for important tasks of the mission, the handling qualities of the aircraft need to be properly designed and tested.

UAS SYSTEM ARCHITECTURE

The basic elements of a UAS are an unmanned aircraft, a data link, and a control station. The interactions between these three systems make up the entire system. When testing for handling qualities in a UAS, it is important to understand and separate the effects of the hardware, software, and the datalink. The hardware component primarily comprises of the stick and rudder pedal dynamics, ergonomics in the control station, and the control surfaces and actuators in the aircraft. The software may contain displays, behaviors, or logic that change how the pilot interacts with the vehicle. Finally the datalink is the primary culprit for introducing time delay and can have adverse effects on the handling qualities of the UAS.

Control Station

The control station is any device or system that supports autonomous or manual control of the RPA. It can be fixed, mobile, hand held, or mounted in another aircraft. The basic functionality of these different control stations is the same and therefore, for simplicity, this paper will only refer to Ground Control Stations (GCS) that contain a basic cockpit. The basic cockpit in a GCS may consist of a throttle, control stick, and rudder pedals as well as any other hardware inputs beneficial to the pilot (landing gear controls, flap lever, munitions arming switch, engine kill switch, Hands-on Throttle and Stick [HOTAS], etc.). The cockpit also has a video feed from the aircraft, normally overlaid onto a HUD. The video feed can be sourced from any number of onboard sensors such as a daylight video camera, Electro-optical/Infra-red (EO/IR) camera or a combination thereof.

To control the RPA, a pilot makes an input into the system (control stick or throttle movement for example), then the signal is processed by the GCS and sent to a data terminal that transmits the signal across the data link (normally radio frequency [RF] or satellite communication). The RPA receives this data using its own data link antennae and processes the data using an onboard computer which outputs a command to the flight controls, resulting in the desired output. An overview of the system is provided in Figure 4.

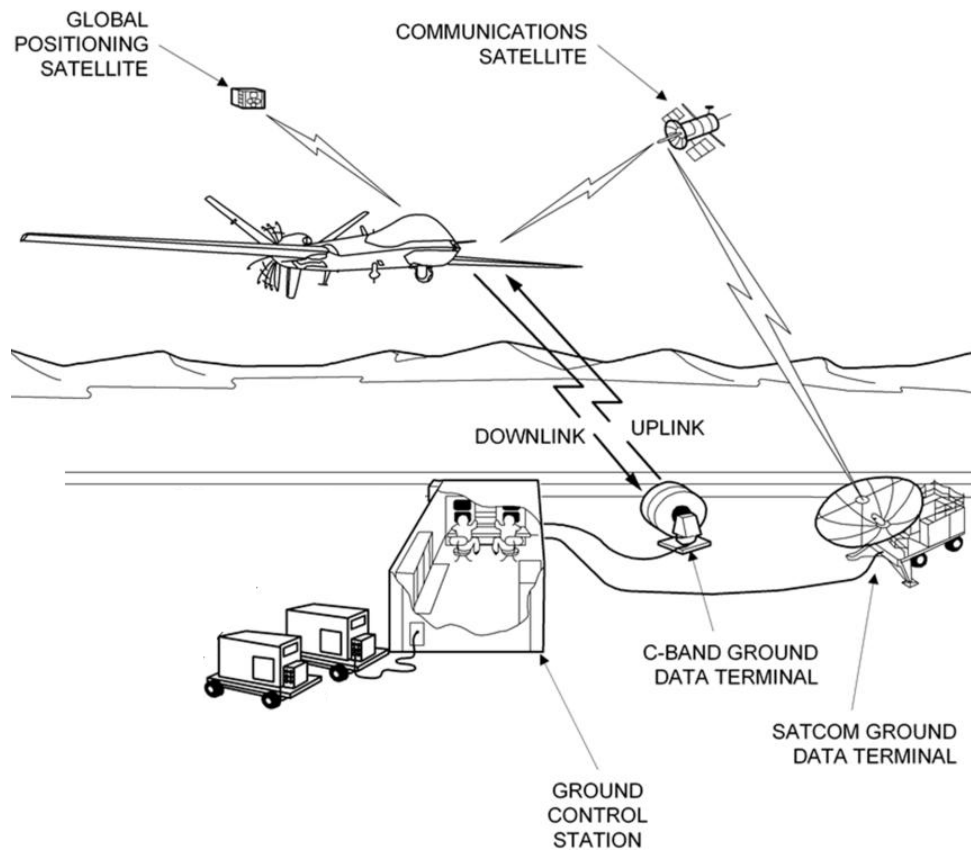


Figure 4 UAS Overview

With today's computers, this process can be accomplished rather quickly, on the order of ~150 milliseconds (ms) for RF data links within Line-of-Sight (LOS) of the RPA. For satellite communications, the latency is approximately 1-2 seconds. While fast, these do not compare with the latency of manned aircraft that exhibit imperceptible time delays, usually less than 5 milliseconds, which is considered a minimum threshold for time delay perceptibility. To account for this delay, the flight control system uses an attitude command system instead of the conventional attitude rate system which will be discussed in the flight controls section.

UAS Cockpit

There are several differences in the UAS cockpit from the manned cockpit that make designing a flight control system more complex than a manned aircraft.

As previously mentioned, a standard UAS cockpit will consist of: a visual display, throttle, control stick, rudder pedals, and other appropriate hardware switches and levers. Removing the pilot from the aircraft reduces the amount of information available to the pilot. Of his five senses, the UAS pilot has only sight to rely on for aircraft control. While taste and smell are still affected by what other crewmember brought for lunch, things we tend to take for granted have all of the sudden gone away or have been replaced – the hum of the engine is substituted by the whir of computers and servers, the crew experiences 1-g at all times, there's no smell of jet fuel, exhaust, and freedom - even vision is reduced to two-dimensions with no periphery. As one wise MQ-1 instructor pilot once said "any resemblance to airplane flying as you know it is purely coincidental."

The pilot control loop for an unmanned system is represented in Figure 5 below, modified from Figure 1:

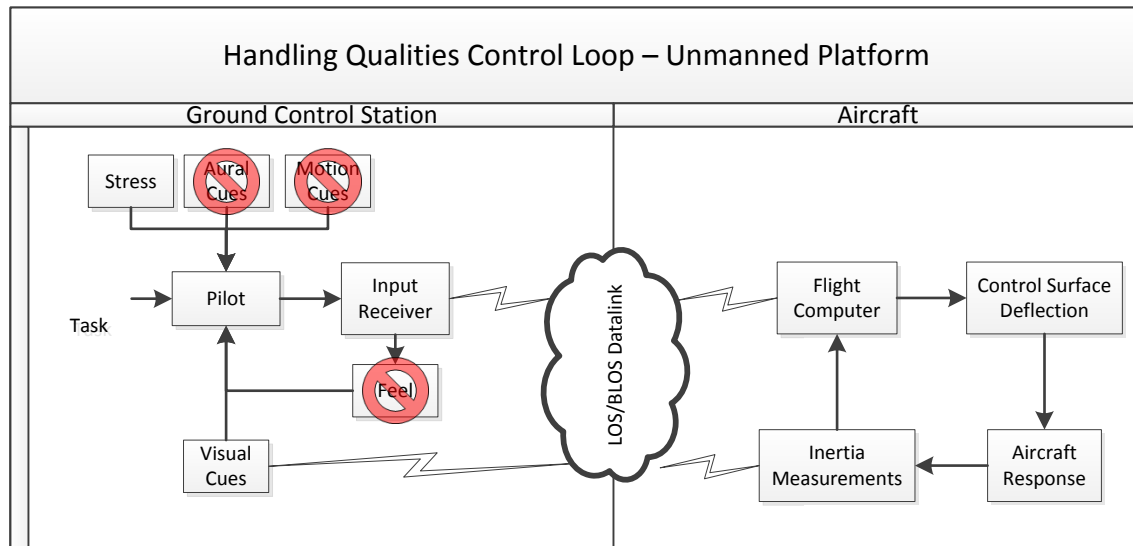


Figure 5 UAS Modified Handling Qualities Control Loop

As previously mentioned, the majority of sensory cues that are present in a manned platform are not available when the pilot is removed from the aircraft. For the MQ-1 and MQ-9 aircraft, visual cues are replaced by a nose camera and a HUD. The nose camera can provide the pilot with terrain features and weather conditions but due to its limited Field of View (FOV), it does not provide great Situational Awareness (SA) for collision avoidance with other aircraft, terrain avoidance during turns or dynamic maneuvers, or the best ground reference for landing. Most RPA, however, have a separate onboard camera attached to a gimbal and operated by another crew member that provides (some) missing situational awareness.

The HUD provides the pilot with important aircraft parameters such as airspeed, altitude, Angle of Attack (AoA), pitch attitude, roll attitude, vertical velocity, engine status, etc. Due to the limited bandwidth of the data link, some of these parameters may be sampled at relatively low rates. This can cause the display to appear “choppy” which adds another degree of difficulty for the pilot when executing mission tasks. On the other end of the scale, parameters that have a high sample rate coupled with a highly sensitive instrument can appear to fluctuate at high frequencies, preventing the pilot from determining the value of the parameter.

UAS Datalink

In order to communicate with the UAS, the aircraft utilizes one or more data links. Data link communication is performed over RF to communicate to the UAS in direct LOS or Beyond Line-of-Sight (BLOS). BLOS communication can be achieved by communicating to the UAS via another platform, whether it is a satellite, a naval ship, or another airborne platform. The BLOS communication increases the amount of latency in the system since the data has to travel further than LOS and has to be processed through various systems. The increased latency results in adverse effects on handling qualities and it is very rare for BLOS communications to be used for high risk handling qualities tasks such as takeoff and landing. Those tasks are commonly performed using a LOS datalink after which a BLOS datalink can be used for operations that are beyond line of sight of the ground station data terminal.

The RPA

The RPA is very similar to manned vehicles in almost every regard with the exception of communication and control. First, removing the pilot from the vehicle creates the requirement for remote control of the aircraft which is accomplished using a data link. Since the aircraft is being manually controlled during critical phases of flight, such as takeoff and landing, redundancy is built into the communication system on the aircraft. Antennae are installed on both the upper and lower section of the fuselage to prevent antennae blockage during turning and both directional and omni-directional antennae are used for additional redundancy. In addition, the RPA flight computer has a built in logic that will autonomously fly the aircraft should the link between the ground station and the aircraft become lost.

Second, the latency of the data link system causes handling qualities issues that are addressed by the use of a different type of flight control system.

UAS Flight Control System

On any aircraft, the latency from pilot input to aircraft response back to pilot input is a large determining factor in the handling qualities of the vehicle. If there is a large latency, the pilot can become out of phase with the aircraft response and develop a PIO which is undesirable for handling qualities.

In a manned platform, the latency is from pilot input to aircraft response, such as that caused by transport time delay in a digital flight control system. In an unmanned platform, the aircraft response has to be downlinked back to the ground control station for the pilot to recognize and react to it. This additional step increases the equivalent system time delay. One common method used in RPA to compensate for time delay is using an attitude-command flight control system. In an attitude-command system the RPA flight controls are commanded by angular commands instead of rate commands. A pilot's control stick input into the system will command a specific pitch and/or roll angle which is sent to the aircraft. When the aircraft receives that command, it uses an onboard control system to deflect the control surfaces based on current vs commanded attitude angle. An example of such a control system is a Proportional-Integral-Derivative (PID) controller. This controller uses a control loop to continuously deflect the control surfaces to reduce the error between the commanded and actual attitude of the aircraft. Anytime the commanded angle is different from the aircraft angle, the controller will deflect the control surface based on the sum of its proportional, integral, and differential gain values. An example PID controller is shown in Figure 6.

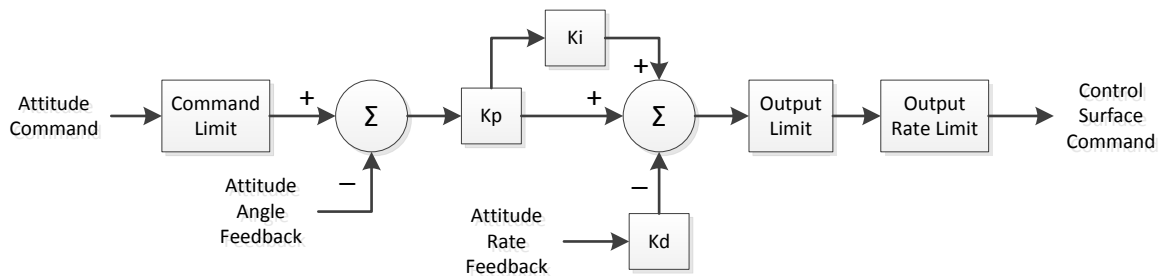


Figure 6 PID Controller

The proportional term provides a component of the control surface deflection by multiplying the proportional gain value by the difference between commanded and actual attitude angle. The

integral term is the sum of the error between resulting attitude angle and command over time multiplied by the integral gain value. The differential term is the slope of the error over time multiplied by the differential gain value. Adding all three terms together yields the control surface deflection value. This value, however, is usually limited by output limits and output rate limits.

Unlike the flight control system on a manned platform, rapid changes in stick deflection do not always equate to the same rate of aircraft response. The onboard processor will command larger control surface inputs for larger deltas between commanded angle and current angle but there is generally an error limit to how large the delta can be. For example, if the error limit is $\pm 10^\circ$ for pitch, an input of $+20^\circ$ pitch from a 0° pitch angle will result in the processor using a delta value of 10° instead of 20° . Additionally, the onboard control processor normally has a rate limiter which prevents large changes in attitudes rates from occurring. With these two limiters, it is more difficult for the pilot to receive proper feedback from his control stick inputs.

Another method used to control an RPA involves commanding roll attitude (ϕ) with lateral stick and flight path (γ) with the pitch stick in the longitudinal axis. A simple way to think of a γ/ϕ -command flight control system is as a shortcut to achieve a desired effect. The pilot controls flight path directly using the Flight Path Marker (FPM) to control the velocity vector in the longitudinal axis, and controls roll using lateral stick to command desired bank angle. Throttle controls airspeed for front-side of the power curve maneuvering. The pilot's task is reduced to pointing the aircraft to an end state and the aircraft responds, essentially freeing the brain from the task of using angles or other parameters to model and effect flight path.

Recent research at the Air Force Test Pilot School has even used a similar principle to employ predictive cueing to compensate for time delays up to 2 seconds. Projects HAVE PIRATE and HAVE ORACLE experimented with lead-compensation algorithms on a surrogate variable-stability Learjet (SVS) and demonstrated the ability to control the VSS with considerable time delays. Although the closed loop control systems modeled were attitude command, the lead compensators used predictive FPMs which represented the vehicle's velocity vector up to two seconds in advance of the feedback image on the HUD. HAVE ORACLE demonstrated Level 1 handling qualities in a closed-loop attitude command flight control system with up to two seconds of latency for tasks at altitude and Level 2 for landing tasks. Handling qualities degradations in the landing phase were attributed to incorrect modeling of ground effect by the predictive cueing algorithm¹¹.

HANDLING QUALITIES EVALUATIONS OF UNMANNED SYSTEMS

Handling qualities must be evaluated for UAS that require pilot-in-the-loop control to some degree. At low levels of automation, it is appropriate to use similar methods to evaluate handling qualities as manned aircraft while recognizing and testing to the unique attributes of the entire UAS – the aircraft, the datalink, and the control station. For systems that have higher levels of automation, it may not be appropriate to apply principles developed on manned aircraft. A number of other methods have been developed and researched for highly automated systems; however, they will not be discussed in the following sections.

In order to design a handling qualities evaluation for a UAS, it is important to understand how a pilot interacts with the vehicle, processes information, and compensates for undesirable motions. Two factors which induce undesirable motions are time delay and stick sensitivity. For a UAS, time delay is inevitable and often the question is “how much time delay is there?” Stick sensitivity causes problems in an attitude command flight control system because stick deflection equals pitch or roll attitude, and an over-sensitive control stick may make precise inputs difficult. Often, UAS control stations use Commercial-off-the-Shelf (COTS) hardware with little influence

over factors such as stick deflection, spring tension, and control harmony. Additionally, HOTAS functionality tends to drive the design with handling qualities being an afterthought.

Test Approach

For this discussion we examine a three-phased approach to conducting a handling qualities evaluation that builds from low gain maneuvering to high gain maneuvering to an operationally representative task that yields a Cooper-Harper rating and an insight on whether the aircraft is Level 1, Level 2, or Level 3.

The first phase can be characterized by low gain, low bandwidth maneuvering. In some ways Phase 1 can be thought of as a warm up in which the pilot can qualitatively assess the aircraft handling in a docile environment. In this phase, the pilot can get a first look at time delay, stick sensitivity, and control harmony and be reasonably confident that he can maintain control while observing the bare airframe response. In UAVs, the flight control systems are closed loop, and evaluating bare airframe would be impossible and impractical. Thus, Phase 1 maneuvering would still be accomplished to evaluate the augmented airframe response. Pilots fly open-loop maneuvers such as pulses, steps, doublets, and bank-to-bank rolls in this phase. Additionally, quasi-open loop maneuvers can be flown such as pitch and heading captures. Phase 1 may take all of a few minutes or as long as necessary until the test team is comfortable proceeding to the next phase. For a UAS, Phase 1 will include an evaluation of displays that provide control and performance information for the aircraft flown. A pilot may have the opportunity to fly the aircraft while looking through a number of video sources, if available. Data obtained in this phase is primarily qualitative, but quantitative data can be used to compare to models and validate the flight control system.

Next, Phase 2 maneuvering seeks to explore high-gain, high-bandwidth control of the aircraft. The primary objective here is to seek out and identify handling qualities cliffs in which control appears nominal to a certain extent then rapidly degrades into a PIO situation. Phase 2 evaluations are conducted at a safe altitude which reduces risk if the pilot encounters PIO by allowing the aircrew time to recover the aircraft in case of unexpected behavior. Many avenues exist to achieve this goal; however the lack of senses while flying a UAS mentioned earlier requires some degree of creativity on the part of the test team for planning and execution. One technique used in manned aircraft testing is Handling Qualities during Tracking (HQDT) that involves a target aircraft ahead of the test aircraft that maneuvers randomly for the test aircraft to track. The test aircraft then uses high frequency, high amplitude inputs to aim for zero-error tracking. During this technique the pilot must resist the urge to compensate by making low-gain inputs as the purpose is to explore the entire envelope for maneuvering. This technique is impractical for UAS because the camera FOV is limited and judging distance from the target aircraft is very difficult. Picking a fixed point in space about which to maneuver also lends problems since over time the pilot will inevitably dwell to zero error and may never elevate gains enough to meet success criteria for the test point. One method to elevate gains without dwell is to use the pitch ladders on the HUD combined with the “W” marker, which indicates feedback pitch attitude. Using the pitch ladders, establish two zones UP and DOWN, which are between 0° and 5° pitch, positive and negative, as shown in Figure 7. This is called a Workload Buildup/Boundary Avoidance Tracking (WLB/BAT) task.

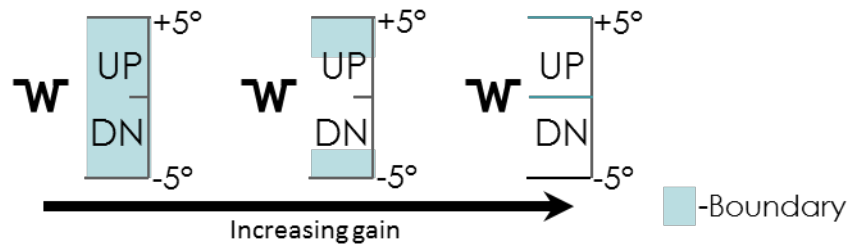


Figure 7 HUD Boundaries for WLB/BAT in the Pitch Axis

Begin the maneuver in level flight then with low frequency inputs maneuver to either the UP or DOWN boundary, as called by the test conductor, who stands behind the pilot and directs the test point. As the maneuver continues, the pilot will build up in workload by making higher frequency inputs and the test conductor will call for the pilot to switch boundaries at irregular intervals. If the pilot is able to maintain the boundary with elevated gains, recover to level flight and establish smaller boundaries, say two and a half degrees wide as shown above, then repeat the WLB/BAT task to the smallest boundary or zero error tracking. If at any point the pilot encounters PIO, call knock-it-off and recover to level flight. For an attitude command flight control system, all the pilot needs to do is neutralize the stick and the aircraft will return to a level, trimmed condition. This same task can be performed in the roll axis using the roll bars on the HUD, as shown in Figure 8.

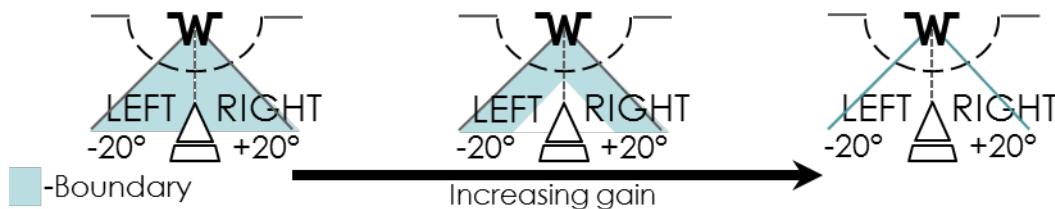


Figure 8 HUD Boundaries for WLB/BAT in the Roll Axis

After performing WLB/BAT tasks, the pilot will assign a PIO rating to the task, which assesses the PIO susceptibility of the aircraft when performing the task. The PIO rating scale, shown in Figure 9, is used to evaluate PIO tendencies and can be used with both Phase 2 maneuvering tasks and Cooper-Harper tasks¹², which will be discussed in Phase 3. At first glance it may seem counterintuitive to fly an aircraft in the manner described above. The reason for this is to explore the edges of the envelope in which the aircraft may be controlled, from the most seasoned pilot to the greenest novice.

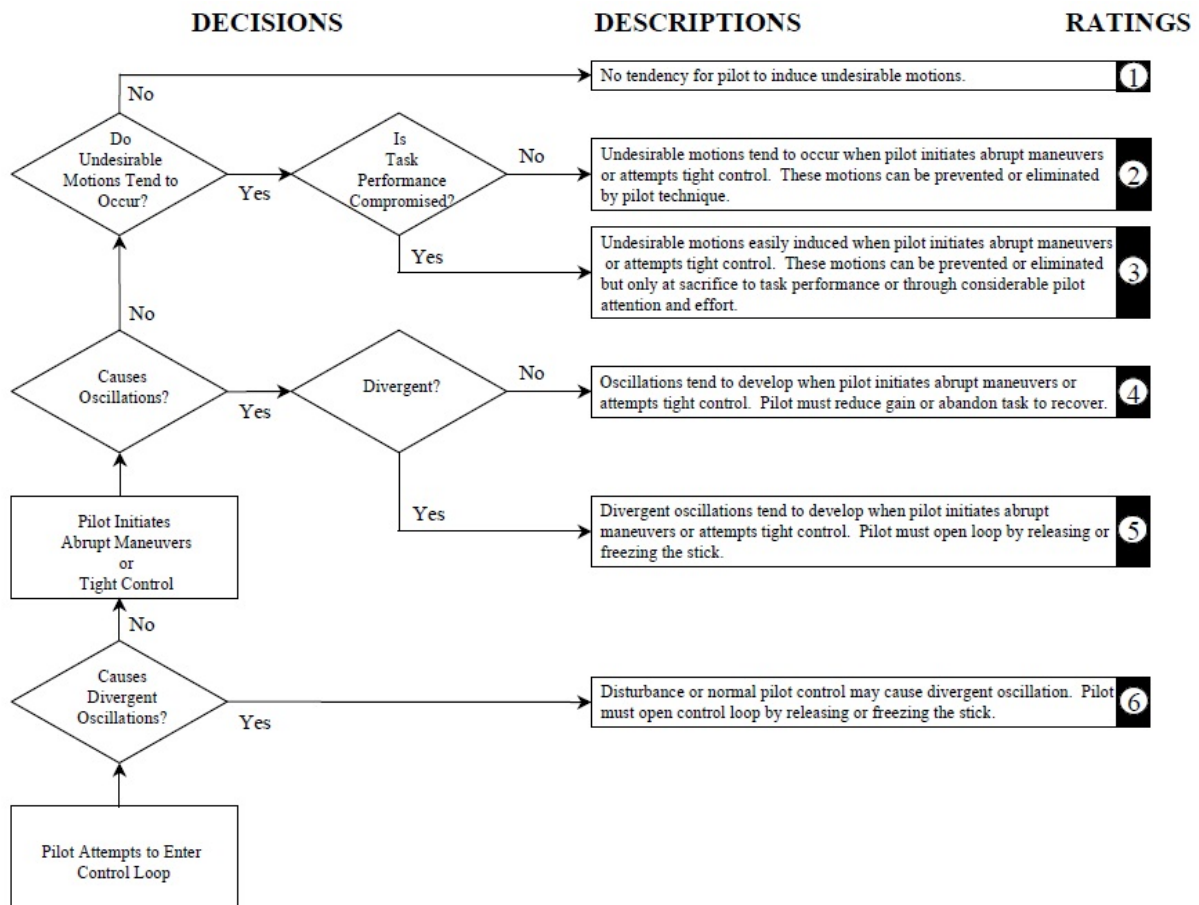


Figure 9 PIO Rating Scale

The final piece, or Phase 3, of a handling qualities evaluation is the operational evaluation using the Cooper-Harper rating scale shown in Figure 2. Desired and adequate performance criteria are assigned to a given task. Performance is assessed as well as workload and pilot compensation in order to yield a CHR. The importance of properly building up to this point cannot be overstressed. With a flight controller that has not been previously characterized, it is not advisable to jump right into a Cooper-Harper task without evaluating low-gain, low-bandwidth maneuvering and checking for cliffs first.

Phase 3 tasks use operationally representative tasks to determine the handling qualities of the system. For manned systems, these tasks can vary from takeoffs, landings, formation with other aircraft, air to air tracking, aerial refueling, bombing runs, to whatever the aircraft's mission demands. For each of these tasks, the pilot is constantly updating his control inputs based on desired aircraft response and actual aircraft response. Tasks such as air-to-air tracking, formation flight, and aerial refueling are specifically difficult for the pilot because the target is moving and not always stable. Additionally when in close proximity to another aircraft, a pilot's gains are naturally elevated due to the consequence of a midair collision. This requires the pilot to maintain very tight control of the aircraft. These tasks are great for Phase 3 because they keep the pilot in the loop with the system, require tight control of the aircraft, and require an elevated pilot workload.

Evaluating Unmanned Systems

To determine operational tasks in the context of a UAS handling qualities evaluation, first define the aircraft's mission. Group 4 and 5 UAS are medium-to-high altitude long-endurance platforms, some with ability to employ weapons. These platforms can execute missions including but not limited to Intelligence, Surveillance and Reconnaissance (ISR), Strike Coordination and Reconnaissance (SCAR), Combat Search and Rescue (CSAR), Close Air Support (CAS), Air Interdiction (AI), and Dynamic Targeting/Time-Sensitive Targeting (DT/TST)¹³. Operational tasks associated with these missions include takeoffs, landings, surveillance of stationary and/or moving ground targets, and weapon deployment on stationary and/or moving targets. Operationally, UAS have not been required to perform aerial refueling, formation flight with another aircraft, or air to air weapons employment. Handling qualities evaluations are only useful for tasks the aircraft has been designed to perform, therefore, testing must focus on those operational tasks that keep the pilot in the loop with the aircraft, require some degree of tight control of the aircraft, and require an elevated pilot workload. It is desirable for an operational task to meet all three criteria.

By design, UAS have highly automated flight control logic which is beneficial for aircraft control but requires extra care when designing a handling qualities evaluation. Therefore the tasks must be designed to avoid scenarios where the performance of the task is measured by the onboard controller and not by the pilot inputs. For instance, one operationally representative task for the UAS is takeoff. Assume the task of the takeoff is to capture a 10 degree pitch attitude after rotation and maintain that pitch attitude until 1,000 feet Above Ground Level (AGL). At rotation speed, the pilot will move the stick to a position that indicates a 10 degree pitch command. The aircraft flight control system will then maneuver the aircraft to this attitude and continuously manipulate the control surfaces to maintain the attitude during climb out. This specific task only measures the pilot-vehicle system to the point of capturing desired pitch after which it measures the aircraft's ability to maintain a pitch command, unless of course stick sensitivity makes it impossible to capture and maintain a pitch attitude. A better task would be to capture an initial pitch attitude at rotation then maintain a climb speed after rotation (± 2 KIAS) until 1000 feet (ft) AGL. In this scenario, the pilot would pull the stick back after rotation, accelerate to the target climb speed, then continuously adjust throttle and/or pitch attitude to maintain that airspeed during the climb. Since this task requires the pilot to constantly update his/her inputs into the system, it keeps the pilot in the loop with the aircraft.

To generate tight control of the aircraft, the task should require the pilot to track an item or parameter that is constantly changing. This will require the pilot continually update his or her input to the flight control system and could uncover issues with latency and/or control system gain and phase margins. An example of such a task where the item the pilot is tracking is constantly changing is tracking a run in line for a weapons deployment. The pilot's HUD has a Flight Path Marker (FPM) that uses aircraft velocities to determine where the aircraft velocity vector is pointed. For weapons employment, the FPM is used to allow the pilot to approach the target from a known direction to ensure the bomb can be delivered on target. The FPM as shown in Figure 10 can be moved laterally onto the run-in line by adjusting the roll angle and/or yaw angle of the aircraft. The run-in line acts as a fixed bearing line from the target. Since it is a fixed line, the pilot has to constantly update the aircraft path of travel by making roll and yaw inputs. Having a changing item for the pilot to track requires the pilot to maintain tight control of the aircraft. Operationally, this task is usually accomplished over BLOS datalink with significant time delay. Thus this task should be performed in both LOS and BLOS configurations in order to provide an accurate picture of aircraft handling qualities.

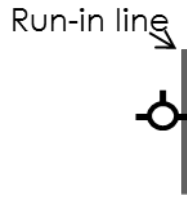


Figure 10 FPM for Bombing Run

Tying in all three factors, operational tasks can be setup to properly test the handling qualities of the system. Example operational tasks for attitude command flight control systems are provided in Table 3 below.

Table 3 UAS Handling Qualities Tasks

Task	Suggested Performance Criteria (Desired/Adequate)	Comments
Takeoff	<ul style="list-style-type: none"> Pitch angle at rotation ($\pm 0.5/2.0$) Airspeed during climb to 1,000 ft AGL (± 2 KIAS/3 KIAS) Runway tracking during climb to 1,000 ft AGL ($\pm 2^\circ/5^\circ$) 	Avoid using pitch angle throughout takeoff for attitude command systems. Targeting airspeed tasks the pilot to use both pitch and/or throttle
Normal Landing	<ul style="list-style-type: none"> Airspeed during landing approach (± 2 KIAS /4 KIAS) Glideslope relative to GLS (one-half dot / 1 dot) Lateral dispersion from runway center-line at touchdown (6 feet / 20 feet) 	Not advisable to perform a “spot” landing since peripheral cues are not available and may risk driving nose wheel into the ground first.
Lateral Offset Landing	<ul style="list-style-type: none"> Same as normal landing 	Lateral offset increases pilot workload to correct for offset
Vertical Offset Landing	<ul style="list-style-type: none"> Same as normal landing 	Vertical offset increases pilot workload to correct for offset
Surveillance of Moving Target	<ul style="list-style-type: none"> Depression angle of video camera ($60-80^\circ$ / $45-60^\circ$) 	Gimbaled video systems normally have limitations on depression angle so the pilot must judge lateral distance, vertical distance, and roll angle to stay within camera limits
Weapon Deployment (using run-in line)	<ul style="list-style-type: none"> FPM tracking to run-in line (within FPM circle / within FPM wings) 	Pilot must attempt to keep the FPM on the run-in line from tracking to release of weapon

Design Methods to Improve Handling Qualities of Unmanned Aircraft

We have just spent some time talking about how to perform a proper handling qualities evaluation, culminating in a rating which assesses how well the flight controller was designed to accomplish a given mission. In this section we will discuss design considerations to improve handling qualities. As previously mentioned, stick sensitivity produces undesirable effects for UAS handling qualities. Stick sensitivity is an easy problem to solve if considered early in the design

of the control station. Software design should provide ability to program different dead band, roll, and pitch angle commands per stick deflection. In addition to software, the flight control hardware should have some allowances for breakout force and spring tension adjustment. Each of these parameters can be tested in a Software Integration Lab (SIL) or Hardware in the Loop (HITL) facility at relatively low cost. Additionally, these should be tested early in the design process to assist in eliminating potential handling qualities issues that may be encountered later during flight test, and will be exponentially more expensive to fix.

Other ways to improve handling qualities include improved visual cues, lead compensators, robust designs for flight critical hardware, and improved trim systems.

The pilot's loss of sensory cues when flying a UAS requires sole reliance on visual cues to perform flight critical functions such as takeoff and landing. Video cameras that provide a visual display for the pilot are generally limited in field of view, restricting peripheral vision. Determining height above ground becomes more difficult especially lacking feel for ground effect, hearing the engine roll back to idle, or sense rate of touchdown. Even sink rate prior to touchdown is difficult to judge – ground rush through a narrow field of view usually appears quite a bit faster than with peripheral vision. To aid in compensating for this, UAS designers can add a laser altimeter to help reduce landing mishaps. The laser altimeter provides the pilot with an accurate measurement for height above ground so the pilot can better determine when to flare and when the aircraft is on the ground. Another improvement that can be made to the system is to provide peripheral vision by adding side displays in the cockpit next to the main forward facing video feed. These side cameras, fed by either additional cameras on the aircraft or by a graphics simulator, can provide the pilot additional visual cues to determine distance from the ground. If peripheral graphics are to be used, they must blend exactly with the nose camera FOV and display visual information at the same framerate as the picture being displayed through the nose camera; otherwise they may become distracting and degrade handling qualities.

Visual cues can also take the form of lead compensators, which give the pilot trend information of what parameters, either input or output will be in the future. For the attitude command system already described, an example of this is a pitch command marker. Since aircraft pitch, even without time delay, will not instantaneously reach a steady state, an aircraft pitch command marker can be very useful in providing lead compensation information to the pilot to close the loop around pitch. In critical phases of flight, such as takeoff and landing, having this information frees up bandwidth for the pilot to perform the task more precisely.

Trim systems for attitude command flight control systems allow the aircraft to fly at a given attitude angle even when the control stick is in the neutral position. For instance, if the pilot wants the aircraft to climb at a 5° pitch angle, the pilot can trim in 5° and center the stick to the neutral position allowing the aircraft to maintain the commanded 5° pitch trim. This reduces pilot workload considerably such that the pilot need not hold forces on the stick for a given attitude. During landing, the pilot positions the aircraft on a target glideslope (normally 3° from the desired touchdown point) and maintains the glideslope until the roundout and flare. Without the trim system, the pilot would have to maintain forward stick inputs to keep the aircraft in a negative pitch angle that corresponds to the target glideslope. The pilot would then have to move the stick from a forward position to an aft position during the flare, through the stick's dead band. This transition through the neutral position can lead to undesired inputs since most control sticks are designed with some amount of breakout force required to move the stick out of the neutral position. Therefore, using the trim system, the pilot can trim in a negative pitch angle corresponding to the desired glideslope then the pilot only needs to apply aft stick from the neutral position to accomplish the flare, making this action similar to how one would flare a manned aircraft.

Further improvements can be made to the trim system to allow finer, small amplitude changes to the trim without moving the control stick by using a trim “hat” switch, as seen on most modern manned aircraft control sticks. With the hat switch, making finer trim adjustments with the thumb is more precise than moving the entire stick, especially for pitch adjustments less than one degree. Although most pilots are taught early in training not to fly the aircraft with trim, for an attitude-command system it makes sense and can reduce workload considerably. A common technique for flying an approach to landing is to trim 2.5-3° nose low and push or pull as required to maintain glidepath and airspeed until the flare. This assists the pilot in having only a small amount of aft stick pull required for the flare, resulting in a smoother roundout. The downside to this is that the pilot spends much of his time on approach flying the aircraft out of the trimmed condition, which increases workload. If the hat switch were available to make finer pitch adjustments while keeping the stick neutral, only a minimal workload would be required until the roundout and flare, at which point the stick would be neutralized and more mental and physical capacity would be available to the pilot for timing the roundout and flare. The MQ-9 Advanced Cockpit GCS test pilots practiced this technique in the simulator and found it to be very reliable.

SUMMARY AND CONCLUSION

Handling qualities testing has been instrumental throughout the history of aviation in identifying deficiencies in piloted control. The use and popularity of unmanned systems has created a substantial growth of UAS in the military and commercial sector. Although automation is ever increasing on these systems, there are instances which require and will continue to require pilot in the loop control. Common aspects of the UAS mission still require pilot-in-the-loop control such as takeoff, landing, and weapon deployment. Therefore, it is necessary to evaluate the handling qualities of these systems to identify any difficulties in control whether in normal operation or in “corner cases”. Flight test methods continue to evolve to evaluate handling qualities in harmony with the tried and true methods used in past flight test programs. UAS have unique considerations which must be accounted for in evaluating handling qualities. Similarly, if the level of autonomy is appropriate for a given task, manned aircraft test techniques can be adapted to evaluate handling qualities in unmanned systems.

UAS use an external, stationary controlling station which removes the pilot from the aircraft thus removing most sensory cues from the pilot, namely proprioceptive, aural, and visual. Coupled with datalink delays and display configurations, it is essential to understand what methods are available to compensate for stolen cues. Particularly, consideration must be given to the angle-command flight control system under test, whether θ or γ , and how a task should be designed to evaluate it. Angle-command flight control systems have been proven to improve handling qualities in unmanned aircraft by mitigating some of the effects of datalink delay; however, there are other means to improve handling qualities in unmanned aircraft. Some of these involve lead compensators and improved trim mechanisms. Consideration to designing handling qualities should be given early in the design process and often in the test process.

APPENDIX A: ACRONYMS

AFRL	Air Force Research Laboratory
AGL	Above Ground Level
AoA	Angle of Attack
AUVSI	Association for Unmanned Vehicle Systems International
BLOS	Beyond Line-of-Sight
CHR	Cooper-Harper Rating
EO	Electro-optical
FOV	Field of View
FPM	Flight Path Marker
ft	Feet
GCS	Ground Control Station
GLS	GPS Landing System
HDD	Heads Down Display
HUD	Heads Up Display
IR	Infrared
ISR	Intelligence, Surveillance, Reconnaissance
LOS	Line-of-Sight
ms	Millisecond
OODA	Observe, Orient, Decide, Act
PID	Proportional-Integral-Derivative
PIO	Pilot-in-the-loop Oscillation
PVI	Pilot Vehicle Interface
RF	Radio Frequency
RPA	Remotely Piloted Aircraft
SA	Situational Awareness
SUAS	Small UAS
SVS	Surrogate Variable-Stability
TAL	Takeoff and Landing System
TD	Test Director
UAS	Unmanned Aircraft System

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